

Gravity, Turbulence, and Star Formation

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Abstract. The azimuthal power spectra of optical emission from star formation and dust in spiral galaxies resembles the azimuthal power spectra of HI emission from the LMC. These and other power spectra of whole galaxies all resemble that of velocity in incompressible Kolmogorov turbulence. The reasons for this are unknown but it could be simply that star and cloud formation are the result of a mixture of processes and each gives a power spectrum similar to Kolmogorov turbulence, within the observable errors. The important point is that star and cloud formation are not random but are correlated over large distances by forces that span several orders of magnitude in scale. These forces are probably the usual combination of self-gravity, turbulence, and compression from stellar winds and supernovae, but they have to work in concert to create the structures we see in galaxies. In addition, the identification of flocculant spirals with swing amplified instabilities opens the possibility that a high fraction of turbulence in the ISM is the result of self-gravity.

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1. Introduction

Many recent studies of ISM gas have shown correlated behavior over a wide range of scales. These observations include power spectra of HI emission in our Galaxy (Dickey et al. 2001), the SMC (Stanimirovic et al. 1999) and the LMC (Elmegreen, Kim, & Staveley-Smith 2001), in addition to many other gas tracers, including molecules (Stützke et al. 1998) and dust (Stanimirovic et al. 2000). A review of these and other correlated properties of the ISM is in Elmegreen & Scalo (2004).

We are interested in correlations specifically related to star formation. Algorithms using nearest-neighbors and cell counting methods find star cluster hierarchies up to kpc scales in many galaxies (Feitzinger & Braunsfurth 1984; Feitzinger & Galinski 1987; Battinelli, Efremov, & Magnier 1996; Elmegreen & Salzer 1999; Heydari-Malayeri et al. 2001; Pietrzynski et al. 2001). Unsharp masks of optical images also show self-similar structure from tens of pc to multi-kpc scales (Elmegreen & Elmegreen 2001), as do auto-correlation functions (Harris & Zaritsky 1999; Zhang, Fall, & Whitmore 2001), which go up to

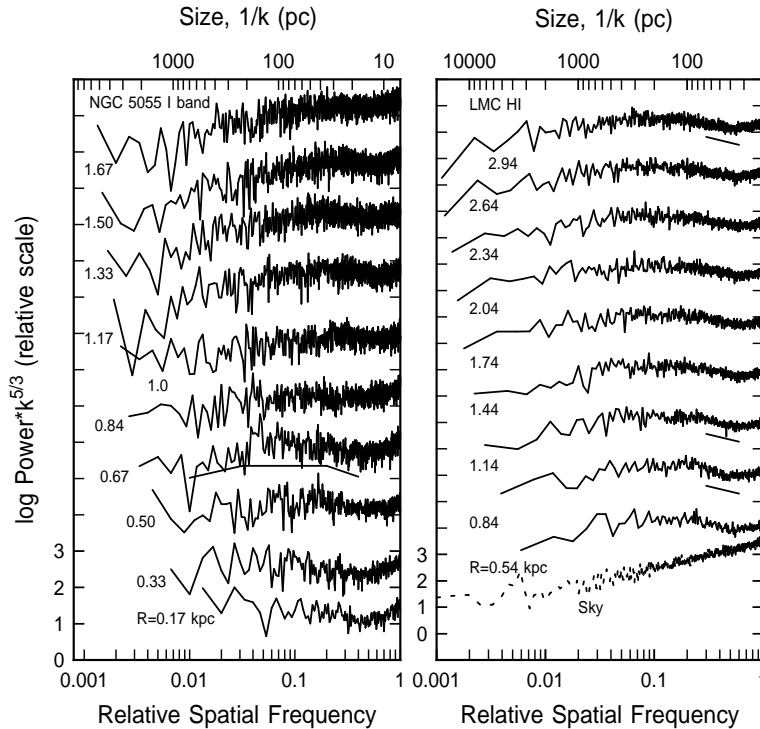


Figure 1. A comparison between the power spectra of optical emission from the flocculent galaxy NGC 5055 and HI emission from the LMC. Power spectra have been multiplied by $k^{5/3}$ to flatten any portions that have the same slope as Kolmogorov turbulence.

about a kpc. Self-similar structure also goes down to sub-parsec scales inside nearby regions (Testi et al. 2000), making the definition of a unique “cluster” sometimes difficult.

These patterns are apparently present as long as the regions are younger than a crossing time, regardless of scale (Elmegreen 2000). After this, random and orbital motions smooth out the stellar positions.

2. New Results

We have recently found that flocculent spiral arms in galaxies have a power law power spectrum too (Elmegreen et al. 2003a,b). This is observed in azimuthal scans of optical intensity in several passbands, and in scans along density wave spiral arms. The azimuthal scans also show the spiral density waves, which are the most obvious features seen directly by the eye, but the density waves are confined to the lowest few wavenumbers in power spectra, as predicted by density wave theory (Bertin et al. 1989). At higher wavenumbers, grand design spiral galaxies look the same as flocculent galaxies in their power spectra.

Figure 1 shows a comparison between the power spectra of the azimuthal scans of the optical emission from the flocculent galaxy NGC 5055, using I band data from HST, and the HI emission from the LMC. To make a slope of $-5/3$ easier to see, we multiplied each power spectrum by $k^{5/3}$ so that a Kolmogorov spectrum of $k^{-5/3}$ would look flat. Each scan corresponds to a different radius, as indicated, and a scan through the sky around the LMC, where the HI emission is very weak, is shown at the bottom right. The power spectra of these two galaxies look remarkably similar, and the power spectra at each radius look similar too, except for the increasing influence of noise with radius, which makes the spectra look like the sky spectrum. There is a relatively flat part in the center of the power spectra at mid-wavenumber range, where the power spectra have the Kolmogorov slope. Also for both galaxies, the power spectra systematically dip down and up at high k . This dip could be the result of unresolved structure: stars and unresolved clusters in the case of NGC 5055 and perhaps unresolved HI clouds in the case of the LMC. It is also possible that the dip in some cases is the result of a transition from 2D structure on large scales (on the left) to 3D structure on scales smaller than the galaxy thickness at the highest k . The line segments in NGC 5055 show slopes of $2/3$, 0 , and -1 , and the line segments in the LMC also have a slope of -1 . The transition from 2D to 3D is expected to change the slope in the power spectrum by 1 , as indicated by the change from 0 to -1 in this figure. Models of the HI power spectra are in Elmegreen et al. (2001) and models of the NGC 5055 power spectra are in Elmegreen et al. (2003b).

The power spectra found in optical images have close to a Kolmogorov slope, although the uncertainties are large because foreground stars introduce distortions that have to be modelled (Elmegreen 2003b). Nevertheless, this result suggests that the standard model for the origin of flocculent arms, namely swing amplified gravitational instabilities (e.g., Toomre & Kalnajs 1991; Wada, Meurer, & Norman 2002), makes structure not only on the characteristic scale of the instability, which is $k^{-1} \sim a^2 / (\pi G \Sigma) \sim \text{kpc}$ for wavenumber k , velocity dispersion a and mass column density Σ , but also on much smaller scales, down to the limit of optical resolution (which is essentially the limit where the power spectra are dominated by individual stars, unresolved clusters, etc.).

If gravitational instabilities are directly or indirectly related to most of this structure, and perhaps even to the resulting star formation that is observed in the optical surveys, then these instabilities could be an important energy source for ISM motions. Widespread instabilities have an available power density that is approximately the energy density of the ISM multiplied by the instability growth rate of $\sim \pi G \Sigma / a \sim 1/30 \text{ My}$ for small Toomre Q . This power density is $\sim 10^{-27} \text{ erg cm}^{-3} \text{ s}^{-1}$ if the conversion to motion is highly efficient. It is an order of magnitude lower than the power density available from supernovae, including their low (0.1) efficiency (Mac Low 2002), but may dominate the energy sources on the largest scales (Crosthwaite, Turner, & Ho 2000).

Numerical simulations of galaxy disks do indeed find reasonable rms velocities from repetitive gravitational instabilities (Thomasson, Donner, & Elmegreen 1991; Fuchs & von Linden 1998; Bertin & Lodato 2001; Wada & Norman 2001; Wada, Meurer, & Norman 2002; Huber & Pfenniger 2001). The resulting structures may be scale-free as well (Huber & Pfenniger 2002).

3. Implications for turbulence

Sources of turbulent energy in the ISM span a wide range of scales. In a compilation by Norman & Ferrara (1996), the largest scale was powered by superbubbles, but it may be that gravitational instabilities are important on large scales too. Studies of the largest HI clouds in the inner galaxy suggested long ago (Elmegreen & Elmegreen 1987) that virialized motions account for ~ 0.5 of the random kinetic energy in midplane HI. The largest CO clouds are virialized too (Heyer et al. 2001), and if they also represent ~ 0.5 of the total molecular mass, according to the cloud mass spectrum, then half of that internal kinetic energy is gravitational also. Because most molecular clouds are parts of giant HI clouds, at least in the Carina arm (Grabelsky et al. 1987), even a good fraction of the GMC cloud-to-cloud motions could be virialized motions.

The shocks of spiral density waves could stimulate turbulence also. Zhang et al. (2001) suggest that a spiral wave has driven turbulence in the Carina molecular clouds because the linewidth-size relation is not correlated with distance from the stellar energy sources. The mechanism for this driving is unknown but it could be gravitational if the spiral shock triggers an instability (Kim & Ostriker 2001).

The total contribution from self-gravity to the turbulent motion of the ISM is not known, but it could be second in importance next to supernovae. A detailed assessment requires a re-evaluation of both sources considering their distributions, the stratification of the disk, and the efficiency of conversion of directed motions into turbulence.

4. Conclusions

Power spectra of galactic-scale structures have power law forms similar to that of velocity in incompressible Kolmogorov turbulence. The observations permit a range of ± 0.2 around the Kolmogorov slope, and this large range, along with the lack of theoretical predictions about what the density structure should be in compressible, self-gravitating, sheared MHD turbulence, prevent the use of these power spectra as diagnostics for definite physical processes. For example, ISM structures are a composite of shells, comets, self-gravitating clumps, and turbulence-compressed regions, and all of these have about the same power spectra.

What is important is that there is a power law power spectrum at all. This occurs for a wide range of structures ranging from nested shells in the LMC, to dust spirals in galactic nuclei, to flocculent star formation arms in optical galaxies. These structures are self-similar over several orders of magnitude in scale. This observation argues for coherent formation processes, although these processes may involve various mixtures of forces in different regions. The observations also suggest that all of these forces contribute to ISM turbulence.

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